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Proposed Paper: Continuous Improvement in Battery Testing at the NASA/JSC Energy System Test Area

Abstract:

The Energy Systems Test Area (ESTA) at the Lyndon B. Johnson Space Center in Houston, Texas conducts development and qualification tests to fulfill Energy System Division responsibilities relevant to NASA programs and projects. ESTA has historically called upon a variety of fluid, mechanical, electrical, environmental, and data system capabilities spread amongst five full-service facilities to test human and human supported spacecraft in the areas of propulsion systems, fluid systems, pyrotechnics, power generation, and power distribution and control systems. Improvements at ESTA are being made in full earnest of offering NASA project offices an option to choose a thorough test regime that is balanced with cost and schedule constraints. In order to continue testing of enabling power-related technologies utilized by the Energy System Division, an especially proactive effort has been made to increase the cost effectiveness and schedule responsiveness for battery testing. This paper describes the continuous improvement in battery testing at the Energy Systems Test Area being made through consolidation, streamlining, and standardization.

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Biography:

William Boyd started his career in the '70s as a Chemical Engineer with the Propulsion & Power Division at the Lyndon B. Johnson Space Center. He has held positions of increasing responsibility up to and including his present position as Chief of the Energy Systems Test Branch.

Joseph Cook started his career in the '80s as an Aerospace Engineer with the Propulsion & Power Division at the Lyndon B. Johnson Space Center. He has held positions of increasing responsibility within Government and industry up to and including his present position as Mechanical Engineer Staff at Lockheed Martin.

INTRODUCTION

NASA's ability to deal with and overcome technical challenges in leading mankind's exploration of space is well established. Landing men on the Moon, developing a reusable space transportation system, establishing a permanent presence in earth orbit, defining the infrastructure required to explore beyond the Moon, and recovering from tragic setbacks are the highly visible accomplishments of NASA and its industrial partners. The new millennium, however, has brought an added challenge - the need to achieve its technical requirements with decreasing budgets. This has forced all of the NASA organizations to continually investigate and implement improvements in its operating processes.

One NASA organization that has taken on the "continuous improvement" challenge is the Energy Systems Test Area (ESTA), located at the Lyndon B. Johnson Space Center (JSC) in Houston, Texas. Established as the Thermochemical Test Area in 1965, ESTA was originally constructed to provide for the development, evaluation, and qualification testing of orbital spacecraft electrical power, pyrotechnic, propulsion, and auxiliary power systems. To address the hazardous nature of the test operations, ESTA was positioned in a secured location at JSC to insure maximum safety to both on-site and off-site personnel. Figure 1 shows ESTA as it exists today.

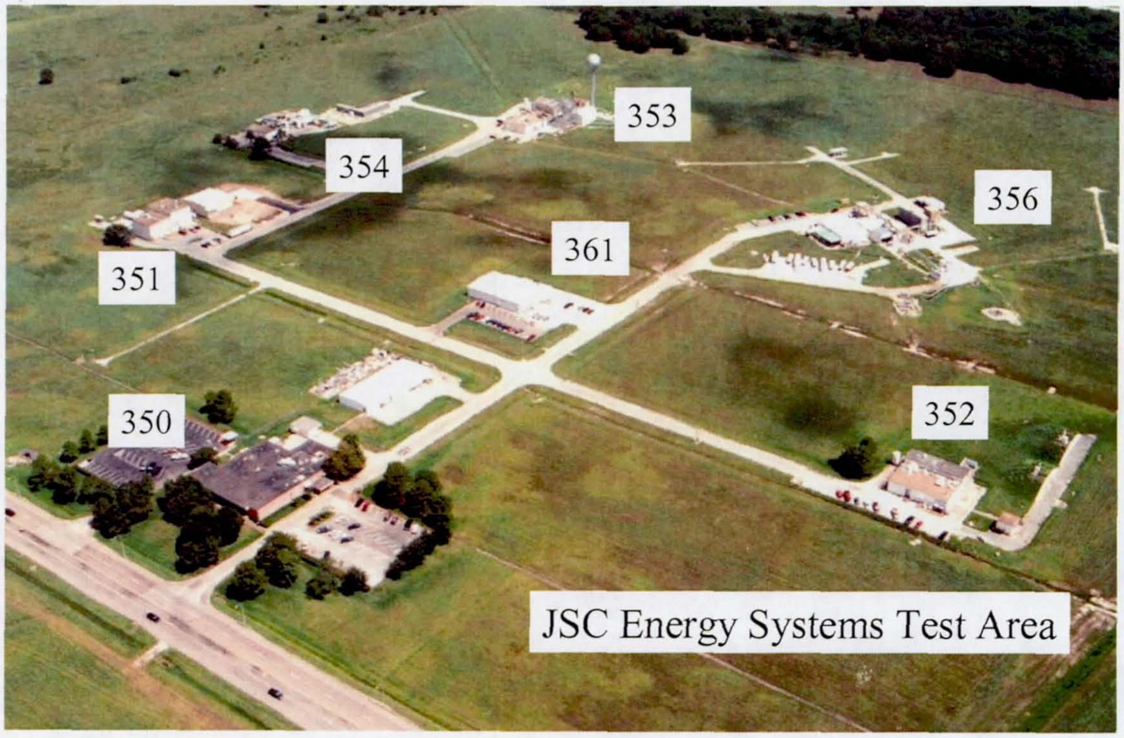

Figure 1. The Energy Systems Test Area

With time, as the responsibilities of JSC have evolved with NASA's space exploration strategies, ESTA has evolved its role, while still making use of its unique capabilities and expertise. Today, six distinct facilities exist in ESTA to enable the safe and effective testing of a myriad of components and systems: an Office, Shop and Laboratory Complex (building 350); a Power Systems Test Facility (building 351); a Pyrotechnics Test Facility (building 352); a Resource Conversion Test Facility (building 353); a Cryogenic Systems and Battery Test Facility (building 354); and a Fluid Systems Test Facility (building 356). Appendix A contains a brief description of each facility.

In accomplishing its mission since 1965, ESTA developed "ways of doing business" that contributed to its ability to successfully support NASA's space vehicle developments. However, given the technology of test support equipment that ESTA continued to use, the work methods involved with supporting testing came to the point where they were no longer fiscally efficient because they relied heavily upon a large workforce of technicians, engineers and product assurance specialists.

NEW WAYS OF DOING BUSINESS

From the beginning, power system support has always been a significant work element at ESTA. ESTA started evaluating fuel cells back in 1966 from companies such as Allis-Chalmers, Pratt & Whitney and General Electric. As of 2003, in addition to continuing to evaluate the latest generation of fuel cells, power systems support has evolved to include a significant amount of battery performance, safety and certification testing for Manned Space Flight applications. Between 1965 and 2003, projects have come under increased pressure from budget, schedule, technology and safety issues, necessitating a fundamental shift in how best to provide a viable test support service. In order to satisfy these often conflicting priorities, ESTA has leveraged a triple faceted undertaking that involves consolidation, streamlining and standardization.

CONSOLIDATING ASSETS

Initial consolidation efforts were focused on the core assets supporting battery testing. The rationale for consolidation is based on three primary points. First, test schedule responsiveness should improve from a higher state of readiness. Second, battery asset utilization should increase through a higher volume of work utilizing the asset base given the shorter turn around time to accomplish a test. Third, core personnel proficiency should expand given the higher concentration of battery testing at one location. Bringing together the core assets should help provide leverage that is not possible with the historical test implementation approach at ESTA.

Historically, testing at ESTA has been spread amongst the five test facilities, with the primary factors governing selection of a location being safety of operations, and asset and personnel availability. Since the inception of ESTA in the early 1960's, the heart of a test facility has been its control room. As shown in Figure 2, the control room of the more recent past was dominated by a central data system (e.g., ModComp) and supporting recorders (e.g., FM tape) that tied into specific test cells by patch boards.

Figure 2 – Facility Control Room Dominated By Central Data System

Often the heart of the facility resulted in being a bottleneck to facility operations. Countless hours were spent for each test program switching setups and verifying end-to-end signal integrity. Data system technology changes over the years have enabled testing in any given facility to move beyond performing only one test a time. As shown in Figure 3, in more recent years the test facilities have been transitioning to individual data acquisition and control stations for each active test cell. This provides for the control room being able to operate at least several, if not a half-dozen, tests simultaneously.

Figure 3 – Facility Control Room With Individual Data And Control Systems

When the personnel can be local with the device under test (i.e., remote testing is not required to address safety concerns), such as for battery performance testing, the systems supporting data acquisition and control are now being distributed into the test cell to further facilitate testing, making it possible to operate several test programs in one test cell and many times that in just one facility. Figure 4 shows one of the several cells that are used for battery testing. This particular cell is environmentally conditioned to provide a suitable environment not only to improve the consistency of battery test results, but also to insure the longevity of the electronics associated with five multi-channel battery test systems that are housed within.

Figure 4 – Test Cell With Distributed Data And Control Systems

Prior to making a change towards consolidating battery test support assets, four separate facilities each with different personnel were involved as the need arose to support different battery test programs at ESTA. The Power Systems Test Facility has supported battery activities through the use of commercial and in-house developed battery test systems, a thermal-vacuum chamber, spot welders and a cell disassembly glove box. The Pyrotechnics Test Facility has provided support with a battery abuse test system, several commercial battery test systems (e.g., Arbin, Cadex and Chrsitie) and spot welders. The Cryogenic Systems Test Facility has supported battery testing with an in-house battery test system and a battery abuse system. And the Fluid Systems Test Facility has supported testing with an in-house battery test system. Additionally, other work areas in the facilities have been used on an as-needed basis when a unique environment is required for a specific test program (e.g., vibration and shock).

Given the inherent limitations of the historical support approach, ESTA management determined battery customers would receive better service by consolidating the various battery test systems from across ESTA into one location (Building 354, Battery and Cryogenic Systems Test Facility). Activities to be supported at this consolidated location include those used for battery performance tests, safety (or abuse) tests and certification for flight tests. The consolidated facility will involve most of the present in-house and commercial battery test systems, battery abuse chambers and support equipment (e.g., spot welders). Some systems and equipment will remain in specific facilities containing unique environmental capabilities until a cost effective approach is devised for setting up similar environments at the Battery and Cryogenic Systems

Test Facility, providing that workload and hazard control requirements warrant buildup of similar assets (e.g., vibration and shock testing beyond design limits).

The consolidation plan for the Battery and Cryogenic Systems Test Facility provides focus for ESTA battery test programs. Many battery test support capabilities will be made ready for quick turn around support of routine tests in order to minimize buildup effort. To date, there are several routine engineering-level battery performance tests being performed: physical characteristics, electrochemical characteristics, effective internal resistance, nominal charge/discharge capacity, rate capability cycling, performance capability cycling at different temperatures, vacuum leak, vent pressure and burst pressure. There are also several routine safety (or abuse) tests being performed: over charge, over discharge, short circuit, high temperature exposure, heat to vent, vibration, drop and crush.

To support these battery tests a strategic mix of in-house and commercial systems have been consolidated that provide for performance as well as safety testing of batteries from below 1 Volt and 0.1 Amps, to above 400 Volts and 500 Amps. In-house systems are predominantly being used where complete understanding of test system failure modes and configuration control is required, such as for flight hardware certification tests. Whereas commercial systems are predominantly being used for quick turnover tests such as engineering performance evaluations of batteries. Test chambers also involve a mix of in-house and commercial environmental systems for thermal testing from –100 °F to +300 °F, as well vacuum testing to levels below $1x10^{-3}$ Torr with a launch vehicle simulated depress and repress rate of ~8psi/min. The in-house test chambers are concentrated on those safety tests exposing batteries to abuse levels so that hazardous byproducts can be controlled, while commercial systems are used for environmental exposure within established design limits.

The long-term plan for the Battery and Cryogenic Systems Test Facility also includes providing storage for all engineering as well as flight batteries at ESTA. Flight hardware must be controlled by required quality documentation. Battery storage environments include room temperature, refrigerated and frozen storage. Temperature controlled storage involves both industrial trailers to house the majority of the larger battery assemblies for projects requiring long term storage, as well as upright refrigerators and chest freezers for individual cells.

STREAMLINING PROCESSES

Streamlining is focused on the process that controls conduct of battery testing at ESTA. The rationale for process streamlining is based on three primary points. First, test support cost should decrease by reducing the tasks associated with getting into test. Second, test schedule responsiveness should also improve by reducing the number of test start tasks. Third, core personnel proficiency should expand by enabling personnel to focus more on the value added tasks of producing test data. The basis for the later point comes from the idea that the more a test team concentrates on core value-added tasks associated directly with producing battery test data the more experience they gain for testing batteries and, thereby, the more skilled the test team will be at achieving a set scope of work for battery testing. Completing the paperwork, systems, and reviews for the test process ahead of time should help overcome drawbacks inherent to the historical test implementation approach at ESTA.

Testing at ESTA follows a General Operating Procedures Manual (GOPM) that defines operations within ESTA. The GOPM documents philosophies that assure safety in operations, methods to comply with ISO9000 requirements, techniques for effective process control in the production of accurate test data for ESTA customers, and methods for assurance of compliance with applicable regulatory authorities. One complete section of the GOPM is dedicated to Test Operations. Figure 5 shows the overall test process followed by all engineering-level battery performance tests before and after streamlining.

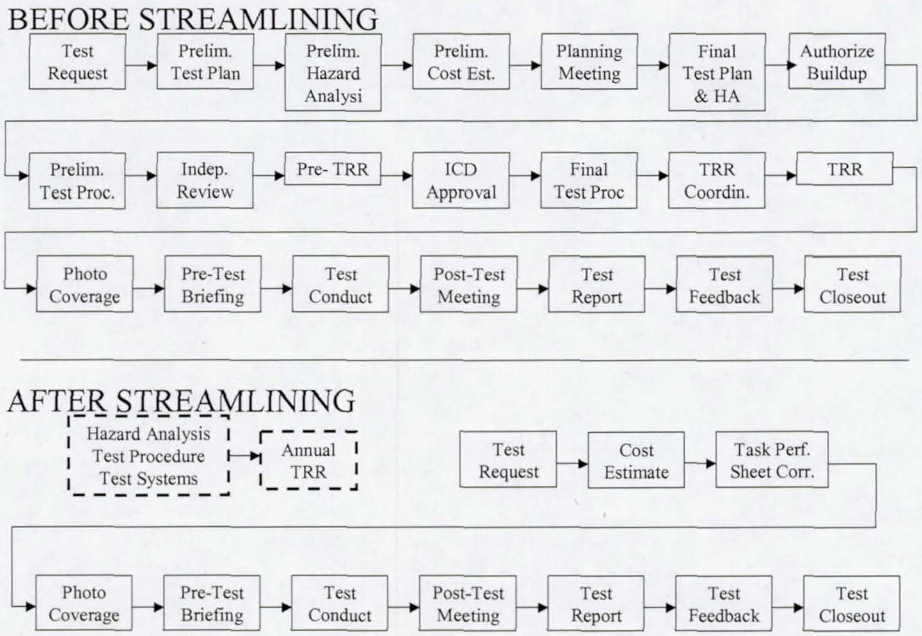

Figure 5 – ESTA Process For Test Operations

The GOPM section on Test Operations provides instructions for preparation and handling of the documents which provide the control and historical records of the test operations activity. The purposes of these documents include authorization to commit resources, outlining of the scope of the resources commitment, procedures for safe and effective production, work direction, configuration and activity records, and a report summarizing the work effort. The basic process steps required to complete a typical test program at ESTA can involve over ten different personnel: Test Requester, ESTA Resources Assistant, ESTA NASA Management, ESTA Technical Area Lead, ESTA Support Contractor Management, Test Director, Facility Engineer, Lead Facility Technicians, NASA Safety, ESTA Safety and Independent Reviewer. Quality Engineering and Quality Assurance are also required if the test is for a flight program.

The majority of the process steps are involved with moving the program along to the point of receiving management approval to start the first test run. 1) The Test Requester prepares a Test Request to initiate test program planning and to request test services, test activity, test support, or general support service work from the ESTA facilities or laboratories. 2) The Test Director prepares a preliminary test plan, attaching a test matrix, instrument planning sheet, calculation planning sheet, mechanical schematic, and any other preliminary information that will assist the facility in preparing for the test. 3) The Test Director prepares a preliminary hazard analysis. 4) The Test Director prepares a preliminary cost estimate. 5) The Test Director conducts an informal Test Planning Meeting to provide the facility with the preliminary information on the test and obtain the facility input required to finalize the Test Plan, Hazard Analysis, and cost estimate. 6) The Test Director prepares and distributes the final version of the Test Plan and Hazard Analysis, providing the facility the information required to begin test stand design and component procurement. 7) The Test Director authorizes and monitors test stand buildup through the use of approved Engineering Orders and Task Performance Sheets. 8) The Test Director prepares and distributes a preliminary Test Procedure. 9) The Test Director arrange for an independent review of the test system and paperwork whereby an Independent Reviewer completes a checklist, identifying actions that the Test Director resolves prior to holding a Test Readiness Review (TRR). 10) The Test Director schedules and holds a Pre-TRR meeting, during which a line-by-line review of all test paperwork is conducted. 11) The Facility Engineer prepares an Interface Control Document, which the Test Director reviews and approves prior to the TRR. 12) The Test Director prepares the final Test Procedure, coordinating with the Quality Engineer to incorporate Mandatory Inspection Points on Quality category tests. 13) The Test Director schedules the TRR, schedules a TRR Board (TRRB) chair, and distributes a review package. 14) ESTA NASA Management chairs the TRR, reviewing a checklist and conducting a walk-through of the test stand. The Test Director completes all actions from the TRRB before proceeding with activities to start the first test run.

After completing all TRRB actions and receiving management approval to start the first test run, the remaining steps involve test conduct and documentation. 15) The Test Director arranges for photo/video coverage of the test article, test stand or test operation. 16) The Test Director holds a Pre-Test Briefing with the entire test team immediately prior to performing the operation, clarifying roles and responsibilities of each team member. 17) The Test Director performs the test per the approved Test Procedure, providing a weekly status to ESTA NASA Management and recording all anomalies observed during the test. 18) The Test Director holds a post-test meeting immediately after each test to verify that all anomalies are documented and the test data are reviewed for necessary corrections. After determining the effects of test anomalies and data corrections on the results of testing, the Test Director determines if the objectives have been satisfied and if a retest is necessary. 19) The Test Director prepares a Task History and, if required, an Internal Note and/or Data Package. 20) Upon publication of the Task History, the ESTA Resources Assistant issues a test close out sheet to the Test Director and a Test Requester Feedback form to the Test Requester for feedback on product (test data) acceptability with respect to safety, performance, cost, and schedule requirements. 21) The Test Director provides the items required to close out the Branch test file and arranges to have any test data stored.

It is easily realized that the overall test process is extensive, which may be attributed to hard earned lessons from the era of highly hazardous thermochemical testing associated with hypergolics and hydrogen/oxygen cryogenics that were ESTA's mainstays during the 60's, 70's and 80's. Given the evolving landscape of the local community, ESTA has migrated away from testing certain hazardous technologies. Since the scope of most battery testing has an overall risk much lower to the community than many previous test programs ESTA has historically been associated with, effort is now underway at appropriately streamlining the historical test process, while maintaining safety of operations. While the guiding principles and required policies are still in force and lived up to the letter of the law, many can be addressed at the beginning of a series of repetitive operations, rather than on an individual basis as each operation is performed.

Initial efforts relative to streamlining are focused, firstly, on the set of process steps involving initial paperwork, system buildups, and management reviews that have historically been a recurring cost associated with getting started into the first test run. For battery performance testing at ESTA, the effort to prepare for testing amounts to approximately one-fourth to one-third of the associated cost estimate. Where an individual Test Plan used to be developed individually for each battery performance test program, now a Test Request with a detailed statement of work serves at the Test Plan. Where an individual Hazard Analysis and Test Procedure were developed, now a pre-approved Hazard Analysis and Test Procedure are in place that covers a specific scope of routine engineering-level battery performance tests.

The efforts associated with consolidating battery test assets and personnel in one facility enables the continued use of existing equipment and expertise for all new battery testing, rather than redeveloping those when needed to run another battery test. Additionally, the management reviews that used to be held numerous times a year for each individual battery performance test are now performed annually, covering the battery test process governed by the pre-approved Hazard Analysis and Test Procedure as well as consolidated test facility and test team. Once a new test request is assigned and an initial cost estimate is agreed to, all that is needed to get into test now is a detailed Statement of Work and Material Safety Data Sheet. A test specific Task Performance Sheet is generated that references the Hazard Analysis and correlates the Statement of Work with the standardized Test Procedure, reducing what may have been a week or more of labor occurring over the course of several weeks, to approximately one day.

STANDARDIZING OPERATIONS

Standardization is focused on the operations involved with fulfilling the customer's statement of work, with initial emphasis being associated with the systems utilized. The rationale for standardization is based on three primary points. First, consistency through the use of the same systems will enable increased quality by allowing for continuous improvement in the associated operations. Second, schedule predictability should increase from reduced risk associated with eliminating buildup uncertainties as well as a better understanding of the issues involved with similar tests, enabling measures to be taken that improve controls. Third, test cost should decrease from repeated use of systems rather than building new systems each time a test is needed. Standardizing the systems used for test operations should help overcome drawbacks inherent to the historical test implementation approach at ESTA.

Systems and equipment at ESTA have historically been categorized as either test (specific to one particular test), facility (permanent facility special capability) or plant (permanent original construction). With the exception of plant and facility assets (e.g., altitude chamber with supporting boiler house and steam system), accomplishing a test program has traditionally required buildups that were oriented on achieving a unique test objective. When the test objective was satisfied and there was not an anticipated need to repeat the test in the near feature, which was more often than not, the buildups were torn down to make room for the next test program and release re-useable assets to the area pool supporting all programs. At times, for certain programs that required an inordinate amount of work to configure originally and were likely to be repeated in a similar fashion in the somewhat near future, a test system would be re-categorized as a facility system (e.g., the Space Shuttle Main Propulsion Subsystem helium pressurization system test system).

Categorization of systems and equipment had inherent implications in the responsibility of who initiated work related to the systems as well as who was responsible for controlling the configuration. When it was practical to convert a test system to a facility system, this provided the opportunity to support future test programs in a quicker fashion and at reduced cost. Test systems and equipment normally met the following criteria: a) suitable for a particular program and no others; b) considerably modified before it would be useful for other programs; c) removed and stored, disassembled, or disposed of after the program. Facility support systems and equipment normally met the following criteria: a) suitable for several different test programs; b) minor modifications if any may be required for any of several test programs; c) remain in place after a program but may be stored temporarily between programs. Plant systems and equipment normally met the following criteria: a) part of the building and its utility systems; b) maintenance services are not a direct ESTA responsibility; c) usually provides indirect support to all test programs without modifications. Table 1 illustrates the categorization practices.

Category	Example	Work Initiation Document	Who Initiates	Configuration Control Responsibility	Configuration Document
Test Systems	Pressurization panel built for specific test article	Test Plan. Test Preparation Sheet.	Test Director	Test Director	Interface Control Document
Facility Test Support Systems	MPS Helium Pressurization System	Engineering Order	Facility Engineer	Facility Engineer	Facility System Book
Plant Systems	Facility Air Conditioning. Facility Electrical System.	JSC Form 930 (Construction of Facilities)	Facility Engineer or ESTB Eng Sup Group	JSC Facilities Division	Facility Drawing Package

Table 1 – Categorization Of Systems Across ESTA

Test specific buildups could leverage items from a standard pool of equipment. Setup and operation of the standard equipment was accomplished using facility documents called Operating Procedures (OP's). The OP's documented operation of all ESTA facility test support systems and equipment which provide direct support during a test, which influence the interpretation of test results, or which require special handling because of safety considerations. Test programs could use the standard equipment to gain efficiencies by simply being able to reference applicable OP's for providing specific steps in the respective test procedures for integrated test operations; however, with the exception of the larger facility systems, continuously reconfiguring the standard equipment also brought along labor costs and schedule duration associated with getting into test.

While there is still a source of standard equipment and accompanying OP's that can be used on unique tests, emphasis for operations supporting battery testing is now being placed on categorizing test systems as facility systems so that they remain ready to use for all future programs. Having more permanent facility system assets in now possible given the number of battery projects being supported by the Energy Systems Division. Systems of particular importance for battery testing include those associated with charge/discharge cycling and safety (or abuse) testing. Over the past two years, ten battery charge/discharge cycling systems, one burst pressure system and three safety systems have been categorized as facility systems. The tests that are now being routinely conducted with minimal test specific buildup include those performance, safety, and certification tests identified in the previous section on streamlining.

LOOKING TOWARD THE FUTURE

Over the past two years the Energy Systems Test Area has made significant strides to increase the cost effectiveness and schedule responsiveness of battery testing by leveraging a triple faceted undertaking involving consolidation, streamlining, and standardization. Test equipment technology changes over the years have resulted in the test facility being able to perform numerous tests simultaneously, provided that the essential assets are consolidated accordingly. As the community landscape changes, ESTA's transition away from test programs perceived as potentially highly hazardous with respect to the local environment to those of lesser risk has enabled historical test processes to be streamlined. The lower risk tests allow process paperwork, systems, and management reviews to be fully addressed ahead of time, providing a heightened state of readiness to support new projects. Battery test requests that used to take several weeks to prepare for test can now be started simply within one day of request approval. ESTA's ability to be this highly prepared results in more battery test project authorizations, which in turn allows for the asset base to be more fully utilized. The continuous facility activity makes it possible to standardize operations related to battery testing. Emphasizing one facility and a common process for battery tests allows focused personnel to become more knowledgeable and better at fulfilling customer objectives. The end result is that battery testing at ESTA can now be accomplished in less time, at less cost and with better results than was possible just a few years ago.

While these improvements provide ESTA near term potential to continue testing battery technologies utilized by the Energy System Division, these improvements, made in full earnest of offering NASA project offices an option to choose a thorough test regime that is balanced with cost and schedule constraints, may not be sufficient for the future. Not only will ESTA need to maintain momentum on the significant strides made thus far, additional progress in each of the three facets will also be needed as ESTA looks toward the future. The first facet, consolidation of existing assets, will continue where deemed appropriate. Additionally, new assets made available through specific program support tasks will be integrated into the mix of facility systems so that sufficient assets are readily available to help future projects avoid costs associated with test buildup. The second facet, streamlining, will expand to include other categories of battery tests, such as abuse and possibly even certification. Streamlining will also have to involve other aspects of the overall test process that are labor intensive, including data distribution, data reduction, and report generation. The third facet of ESTA's undertaking, standardization, will also include system interfaces and test protocols for implementing routinely requested battery performance and safety evaluations. A potential long-term objective may be the establishment of specific test protocols that define a Manned Space Flight (MSF) test standard for batteries.

APPENDIX A

Energy Systems Test Area (ESTA)

- ESTA facilities
  - **Bldg 350** - Administrative offices, mechanical, chemistry, electronics, and calibration shops
  - **Bldg 351** - Power Systems
  - **Bldg 352** - Pyrotechnics
  - **Bldg 353** - Resource Conversion & Harsh Environments
  - **Bldg 354** - Cryogenic Systems and Batteries
  - **Bldg 356** - Fuel Cells, High Pressure Fluid Systems and Clean Room
- Each Facility has dedicated support systems
  - Data acquisition and control systems
  - Gaseous fluid services
  - Liquid nitrogen supply systems
  - Specialized safety equipment specifically suited to its test operations

Building 351 Power Systems Test Facility

- Supports testing of power generation systems and electro-mechanical actuation devices

- A 15 foot spherical space simulation chamber, capable of attaining a hard space vacuum at temperatures ranging from minus 300 to plus 300 degrees Fahrenheit
- An Electro-mechanical Actuator Test and Evaluation fixture that is a hydraulically operated force simulator for testing actuators in the 0 to 20,000 pounds force range

APPENDIX A (continued)

Building 352 Pyrotechnics Test Facility

- Supports testing of pyrotechnically actuated devices and high energy-density batteries

- Explosive loading and handling room, remote test cells, and pyrotechnic storage in earth covered bunkers.
- Battery Abuse Test Stand submits batteries and cells to a temp range of -100 degrees to +300 degrees F at low pressure
- Vibration Shaker System subjects components and systems to random and sinusoidal vibration levels of 11,000 g-lb RMS over a frequency range of 20 to 2000 Hz

Building 353 Resource Conversion Test Facility

- Supports testing of fluid and chemical processes and systems in simulated planetary environments

- 20 foot Hostile Environment Simulation Chamber for testing of integrated subsystems in a simulated planetary environment, including dust, pressure, and temperature.
- 3 foot diameter and 18 inch diameter T/V chambers
- A water flow bench can test fluid system components with flows of up to 15 gal/min and pressures to 1450 psig

APPENDIX A (continued)

Building 354 Battery and Cryogenic Systems Test Facility

- Supports testing of cryogenic components under space vacuum conditions, as well as test and analysis of batteries

- 6 foot and 8 foot diameter T/V chambers
- 6 foot and 2 foot thermal exposure chambers
- A battery test area allows end-to-end battery evaluations, including disassembly, performance testing, and cell chemistry assessment

Building 356 Fluid Systems Test Facility

- Support fluid system tests requiring a variety of fluids, and temperature or vacuum conditioning

- High pressure test stand exposes components and systems to 30,000 psig (hydro) and 10,000 psig (pneumo)
- 5 foot Diameter T/V Chamber simulate planetary surface atmospheric pressure and temperature conditions
- Oxygen/hydrogen Fuel Cell Test Bed
- Class 10,000 clean room and valve shop

AUTHOR BIOGRAPHIES

William Boyd started his career in the '70s as a Chemical Engineer with the Propulsion and Power Division at the Lyndon B. Johnson Space Center. He has held positions of increasing responsibility up to and including his present position as Chief of the Energy Systems Test Branch.

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